RADIOLOGICAL SHIELDING CALCULATIONS FOR AN AIRBORNE FREE-ELECTRON LASER

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ABSTRACT

A preliminary set of Monte Carlo calculations of the crew exposure for the proposed airborne free-electron laser have resulted in a lead shielding mass of approximately 6 metric tonnes. The laser is to be operated only for four training missions per crew per year, with two minutes of laser operation per mission. Beam loss into the cavity walls, the main cause of the crew exposure, is to be kept below 0.01%. The crew will receive about 2.7 R per year, mostly from bremsstrahlung. Neutron dose rates will be negligable by comparison.

INTRODUCTION

Because of the changing world political situation and experience in the Persian Gulf war, an awareness has come about for the need for a rapidly deployable, all-weather defense against tactical ballistic missiles. A directed-energy system that is capable of complimenting the Patriot missile and its upgrades is an airborne laser system. Candidate laser systems include chemical lasers, the diode-pumped neodymium-glass laser, and the free-electron laser (FEL). Each of these laser systems has its advantages and drawbacks; one of the most challenging design problem for the FEL is the radiological shielding.

It is envisioned that the FEL would require over 500 mA of electron beam current at energies of up to 100 mega-electron volts (MeV). The low energy end of the accelerator is near the forward crew compartment and the beam travels down the fuselage of the plane towards the tail (Figure 1). The beam is sent into a device called an undulator or wiggler that produces the laser light and extracts maybe 20% of the energy from the beam. There is then a 180 degree bend.

The beam is then sent through a device called an energy recovery unit, which removes all but about 10 MeV of the beam energy through a deceleration process. This unit is a set of 40 accelerator cavities operated in a mode so as to keep the electron bunches on the negative phase of the RF. It is this part of the system that requires the greatest shielding, because the electrons are moving towards the forward crew compartment. There is then another 180 degree bend, followed by a beamline that carries the electrons to a dump in the tail of the plane.

In this paper we describe the calculations for the energy recovery system. Calculations for the beam dump at the rear of the plane, and for the accelerator (which will not be presented here) indicate that these radiation sources are insignificant by comparison.

SHIELDING CALCULATIONS

Many of the interesting features of the bremsstrahlung energy spectra and angular and dependence are discussed elsewhere[1,2] and we need not go into great detail here. It is sufficient to say angular distribution in a given bremsstrahlung interaction is very forward peaked, with a width on the order of 1/ radians, where is usual relativistic mass factor for the electron. For electrons above a few MeV, the mean free path for conversion

is called the radiation length. In lead it has a value of about 0.4 cm. In aluminum it is about 7 cm. For conversion thicknesses much less than the radiation length, the radiation energy spectrum will have a 1/E shape. After traversing several radiation lengths the energy spectra of the radiation will tend to a $1/E^2$ shape, thus greatly favoring lower energies. Lead is an excellent material to absorb photons at low energy through the photoelectric cross section and that is why it is used for shielding.

Shielding design requirements are described as follows. Based on our experience designing and operating free-electron lasers, we have concluded that it is not reasonable to expect to keep beam losses below 0.01%. Thus, we choose this percentage as a design goal. It is further assumed that crew training can be accomplished with four flights per year per crew, with two minutes of operation per flight. For a 1 A beam current the combination of all these factors gives 2.5×10^{17} electrons lost per year, at some yet-unspecified location along the energy recovery unit. We then required the dose to be below 5 rem/yr, examining all possible locations for the beam loss to occur.
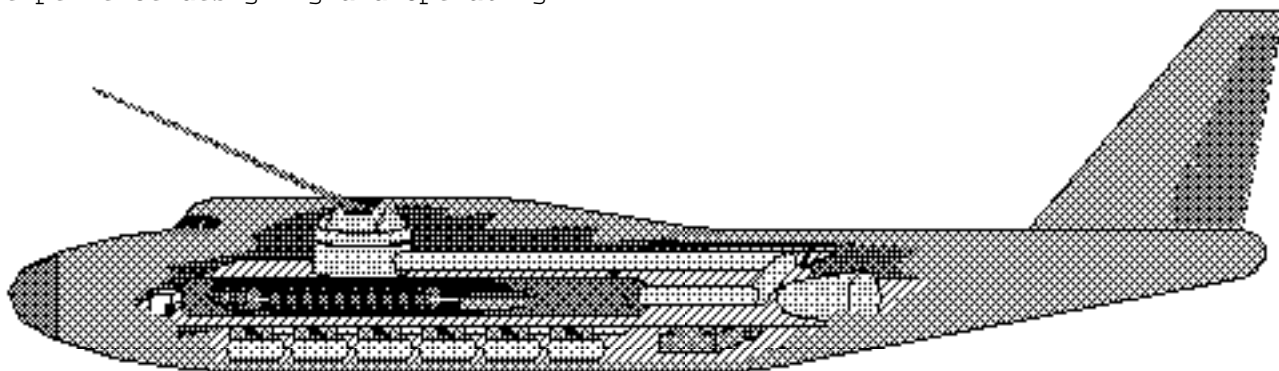

Fig. 1. The Airborne free electron laser conceptual layout. The electron accelerator begins forward, near the crew compartment. Next is the wiggler; finally the beam dump. The RF supplies are below the accelerator. The optical system is very large.

The calculations have been performed using a version of MCNP[3] that can handle the entire electron/gamma shower, including bremsstrahlung, pair production and annihilation, absorption and ionization. The mockup of the airplane for shielding calculation purposes is shown in Figure 2. The skin of the airplane is taken as an ellipsoid of revolution, with an overall length of 71 meters, roughly the size of a 747-class aircraft. The crew are restricted to an area at the front of the plane. The energy recovery system extends from about 4 meters from the crew compartment (where there is a shielding wall) to 44 meters from the crew compartment. The electrons decelerate from an energy of 100 MeV at the farthest point away to 10 MeV at the closest point. The thickness of the aircraft skin is taken so that the mass of the 747 aircraft, minus fuel, is included. Surrounding the aircraft is an ellipsoidal volume of air, included for sky shine determination.

The structure of the energy recovery system and shielding is given in Figure 3. It is taken to consist of a set of 850 MHz aluminum cavities. The bore is 5 cm and the outer diameter is 40 cm. For computational purposes, the flat cavity end walls are included every 1 meter and are taken as 2 cm thick. This translates into an assumption of a 3 mm wall thickness, which is quite thin. Because the walls themselves provide a significant fraction of the shielding, this amounts to a conservative assumption.
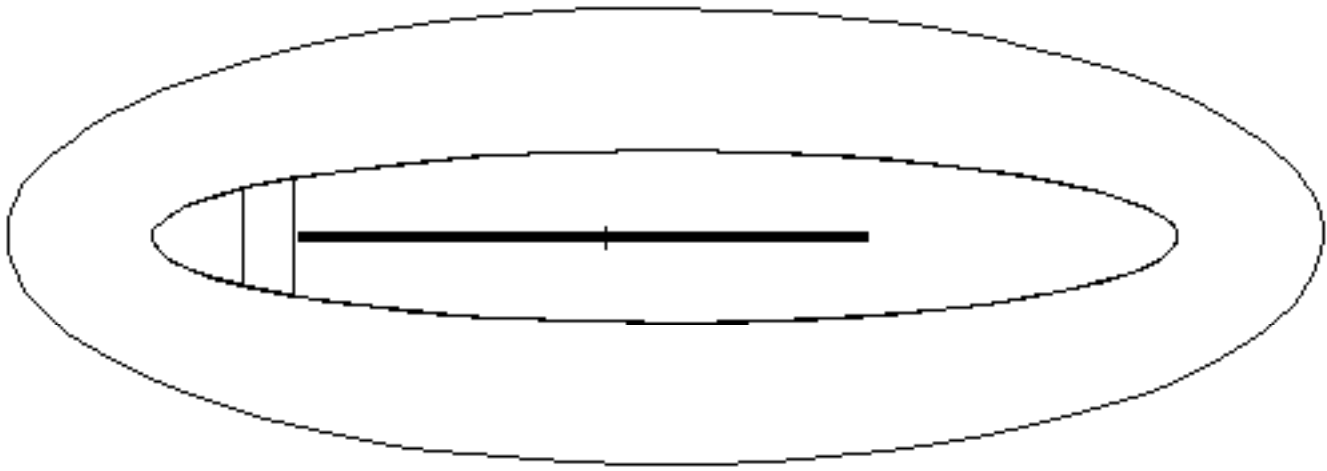
Fig. 2. The geometry used for the simulation of the beam losses in the energy
recovery system. The airplane skin is the inner ellipsoid. An air space extends to
the outer ellipsoid. The electrons slow down from the right to the left.
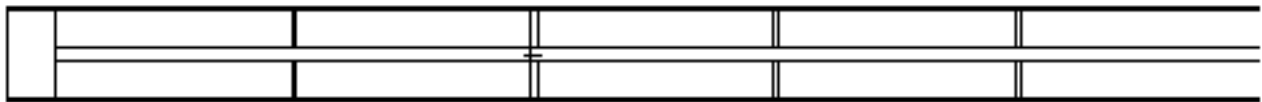

Fig. 3. Closeup of the energy recovery system shielding layout. There is a thick end
wall at the end of the energy recovery system. The system is also surrounded by an
annulus of lead. There is also shielding by a dividing wall.

Shielding consists of three parts. There is an annulus of lead surrounding the unit, nominally at least a few mm thick, and a many-cm thick lead plate at the low energy end of the unit. In practice this plate would surround a 180 degree bend at the end of the unit in a real energy recovery unit, because the beam is taken to the rear of the plane and into a beam dump after energy recovery. The third component is the dividing wall in the airplane, consisting of lead and possibly borated polyethylene (for neutron shielding).

Many sets of calculations were performed, assuming the beam loss to occur at various locations along the

energy recovery system. The thickness of the three lead shields were varied, and the total shielding mass calculated. The best design was chosen as the lightest combination of shielding that would give 2.5 R/yr to the crew for the average over the points along the energy recovery unit. The set of calculational results is given in Figure 4 for the shielding configuration that was deemed best. Here, the shielding consists of a 20 cm thick end shield and a 1 cm thick annulus. There is no shielding wall. The maximum dose to the crew is for losses at 20 MeV along the energy recovery unit. At higher energies the source is at a greater distance from the crew. At lower energies the bremsstrahlung production is much less.
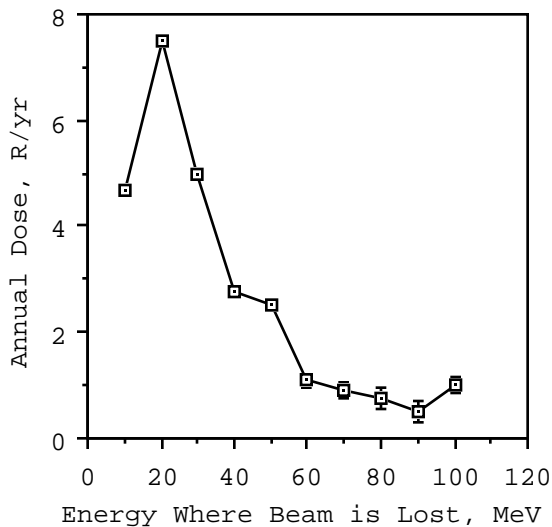
Fig. 4. Dose to crew versus position
in energy recovery system where the
beam is lost. The average over the
whole system is 2.7 R per year.

The shielding is found to be
sufficient for electron losses
anywhere along the unit, keeping the
dose to the crew at 2.7 R/yr, when
averaging the loss over the length of
the energy recovery unit. The total
shielding mass is 6 metric tonnes, the
greatest fraction being in the
annulus. Another set of calculations
showed that the mass quadrupled if the
dose rate was to be reduced to 0.2
R/yr.

We then include photoneutron
production and transport. The neutron
production occurs because of the (,n)
cross section on lead and aluminum,
which we have taken from Ref. 2, and
introduced directly into our MCNP
calculations. Photoneutron energy
spectra were based on the isotropic
emission using an evaporation
spectrum. For aluminum, the quasi-
deuteron component of the energy
spectrum was also included.

In order to perform the calculations
using MCNP, one must first make a run
that tabulates the production of
neutrons on a region-by-region basis.
A second run then transports the
neutrons to the crew compartment The
neutron energy spectrum in our

calculations does not vary with
position, nor does the angular
distribution, which is isotropic.

Figure 5 shows the rate of production
of neutrons in the lead and in the
aluminum regions versus electron
energy. The behavior of the curves is
very much what is expected based on
theoretical and experimental studies
such as Ref. 4. The lead contribution
is much greater simply because its
cross section is much higher. If
copper were used for the accelerator
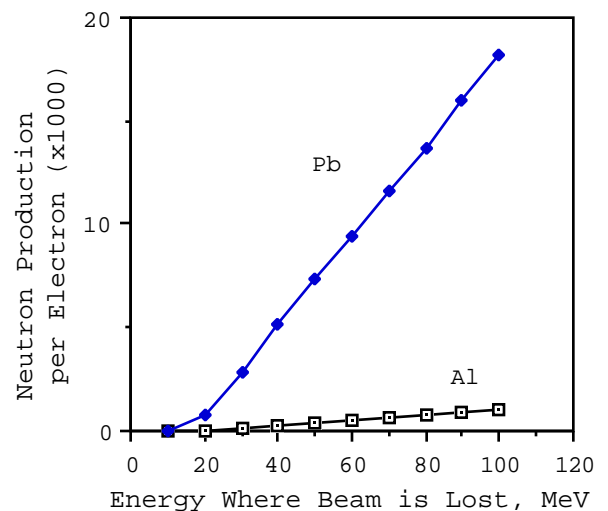construction, the total production of
neutrons would double.

Fig. 5. Production of Photoneutrons in
lead and aluminum regions versus
energy where the beam is lost in
energy recovery system.

Transport calculations showed that the
neutrons are an order of magnitude
smaller in importance to the dose to
the crew in comparison with the gamma
rays. Figure 6 shows the dose to the
crew, again plotted versus where the
electron beam is lost. No additional
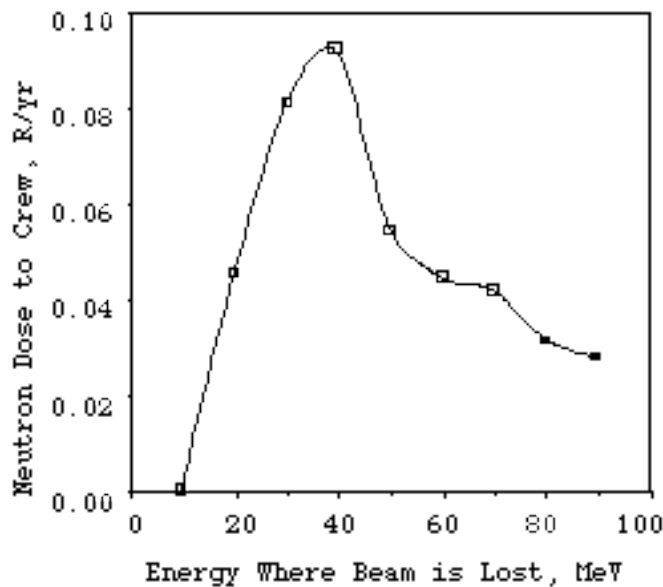shielding was required for the
neutrons.

Fig. 6. Photoneutron dose to crew versus position in energy recovery system where the beam is lost.

CONCLUSIONS

Under the stated assumptions about operation of the airborne FEL, the crew doses can be kept to below 5 R/yr, the limit for radiation workers exposed as part of their normal work routine. The total mass of the shielding is estimated to be about 6 metric tonnes, however, to take the dose rates down another order of magnitude will require possibly four times as much shielding. Thicker accelerator cavity walls will assist the shielding.

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1. J. D. Jackson, "Classical Electrodynamics, Second Ed.", John Wiley and Sons, 1975.

2. W. P. Swanson, "Radiological Safety Aspects of the Operation of Electron Linear Accelerators", IAEA Technical Report Series No. 188, Vienna, 1979.

3. Judith F. Breismeister, Ed., "MCNP - A General Monte Carlo Code for Neutron and Photon Transport, Version 3A", LA-7396-M, Rev. 2, Sept. 1986.

4. W. C. Barber and W. D. George, Phys. Rev., Vol 116, pg 1551, 1959.